Tunability and synthetic lineshapes in high-Q optical whispering gallery modes

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ABSTRACT

We demonstrate novel techniques to manipulate spectral properties of high quality factor ($Q > 10^7$) whispering-gallery modes (WGM) in optical dielectric microresonators. These include permanent frequency trimming of WGM frequencies by means of UV photosensitivity of germanium doped silica resonators; electro-optical tuning of WGM in lithium niobate resonators, and cascading of microresonators for obtaining second-order filtering function. We present theoretical interpretation of experimental results, and examples of applications of these techniques for photonic microwave filtering.

Keywords: Whispering Gallery Modes, Optical filters, Multiplexing Equipment, Optical communications, Optical fiber networks

1. INTRODUCTION

Optical solid state dielectric resonators with whispering-gallery modes (WGMs) possess a combination of unique features including high Q-factors $10^8 - 10^{10}$, submillimeter size, and high mode stability.[1–4] Several effective approaches for coupling light into and out of WGMs have been devised, including a simple and efficient method of using angle polished fiber tips,[5] tapered fiber couplers,[6–8] and prism couplers.[9] These features make the WGM dielectric cavities attractive for application in various fields of research and technology.

In many practical applications resonators with specific resonance frequencies are desired. This, however, is quite difficult to achieve, since the usual method for the fabrication of microresonators based on melting a fiber tip cannot produce a precise, predetermined geometry and, therefore, a precise resonance frequency. Mechanical trimming of WGMs with applied strain[10–12] and temperature[13] tuning have been previously used for the controlled tuning of the resonance frequency in WGM microresonators.

Recently, a technique for WGM resonance trimming utilizing a photosensitive coating was used with microring resonators. In that study, glass microrings were dipped in a polymer coating material and were exposed to UV light. This method produced resonators with relatively small Q (about 800) because of the polimer-induced absorption; but it still allowed large tunability of the optical resonance of the microring, enough for wavelength selective applications.[14]

In this paper we propose two methods for tuning high-Q WGM spectra. One method allows for permanent shifting of the WGM spectra of microcavities made out of compound germanium and silicon oxide glass (or as referred in this paper, germanate glass). The other method allows for fast electro-optic tuning of the WGM spectrum of a cavity made of a crystal possessing a quadratic nonlinearity, such as $LiNbO_3$. Our approach for trimming the frequency of microcavities exploits the photosensitivity of germanate silica glass.[15–17] When exposed to UV light, this material undergoes a small permanent change in structure that alters its index of refraction.[15] This property is used in writing fiber Bragg gratings.[18] In our case, the spatially uniform change in the index of refraction results in a uniform translation of the resonant frequencies of a WGM microcavity.

We have experimentally realized the UV-assisted resonance frequency trimming of high-Q (10^8) WGMs. Approximately 18 GHz permanent frequency shifts were obtained for modes of 1550 nm wavelength with the application of 600 mW power 351 nm radiation from an *Ar*-ion laser. This is enough to tune a resonance over a full free spectral range of the WGM resonator.

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The ability to permanently adjust the WGM spectrum allowed us to construct an optical filter with flatter passband and a sharper rolloff than in a filter based on a single microresonator, which has a Lorentzian transfer function. It was shown recently that coupling the resonators in parallel or in series may result in a passband that is nearly flat.[19,20] In this paper we reported on the demonstration of such a configuration using two tunable, coupled microcavities. By tuning the resonance frequency of one germanium doped cavity very close to the resonance of the second cavity, we succeeded in producing a two-cavity compound filter with a second order filter function.

Wavelength demultiplexing and channel sections in wavelength division multiplexing systems require tunable narrow-band optical filters that are compatible with single mode fibers. Desirable characteristics for the filters include fast tuning speed, small size, wide tuning range, low power consumption, and low cost. WGM cavities are also useful to construct such filters.

We report on the realization of a miniature resonant electro-optically tunable filter. Our filter is based on a micro-disc WGM cavity fabricated from a commercially available lithium niobate wafer. The filter operates at the 1550 nm wavelength regime.

Tunable resonance filters are characterized by the finesse (F) which is equal to the ratio of the filter free spectral range (FSR) and the filter bandwidth. Finesse indicates how many channels can fit in one span of the FSR. The repeatable value of finesse of the $LiNbO_3$ filter exceeds $F = 300$, but in some experiments we have achieved $F = 1000$. The tuning speed of the filter is approximately 10 ns, while the real spectrum shifting time is determined by filter's bandwidth and does not exceed 30 μs. We observed at least -20 dB suppression of the channel cross-talking rate for 50 MHz channel spacing. For comparison, a conventional Fabry-Perot tunable filter may have a finesse of 100, 125 GHz bandwidth, and tuning speed in a millisecond range. Fabry-Perot filters also meet -20 dB channel-to-channel isolation condition for 50 GHz channel spacing.[21,22]

In what follows we discuss properties of WGM-based filters in details.

2. WGM SPECTRA

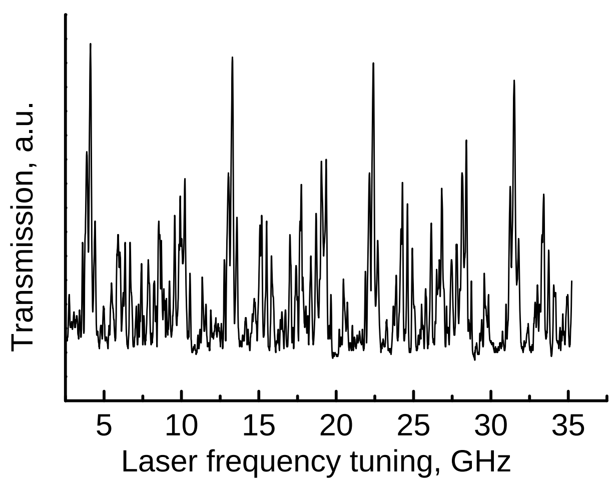


Figure 1. Spectrum of a disk $LiNbO_3$ cavity with spherically shaped rim.

Optical cavities consisting of two or more mirrors are utilized in all branches of modern linear and nonlinear optics. Practical usage of such cavities is technically restricted, especially where high performance of the devices, i.e. high quality factor and high mode stability, is important. Fabrication of good optical mirrors, their alinement, and binding are expensive and difficult tasks.

Open dielectric microcavities are an alternative for usual optical cavities. Fabrication of these microcavities is rather simple and inexpensive. The cavities demonstrate high mode stability and high quality factors.

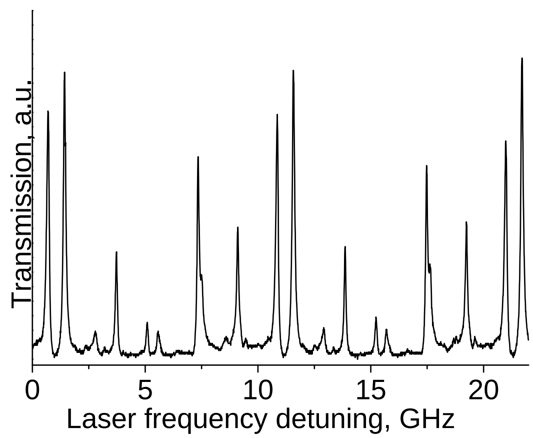


Figure 2. Spectrum of a disk $LiNbO_3$ cavity with torridly shaped rim.

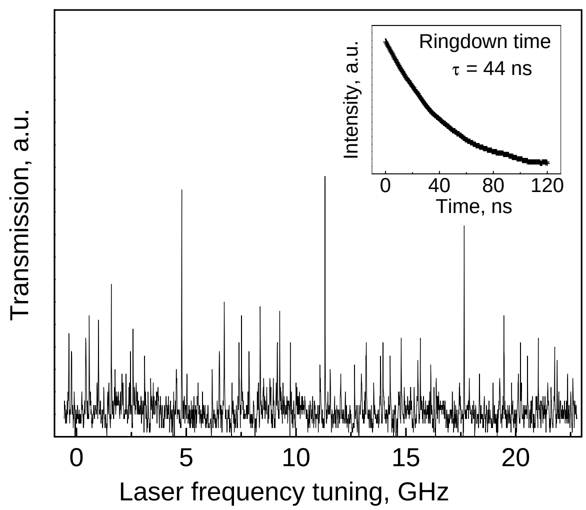


Figure 3. Spectrum of a disk $LiNbO_3$ cavity with conically shaped rim. Inset: ringdown time of the excited WGM mode of the main sequence, corresponding Q-factor is approximately 5×10^7.

However, there are significant differences between properties of open dielectric microcavities and conventional optical cavities constructed of mirrors. Originally proposed spherical whispering gallery mode microcavities (microspheres) are "over-moded", with a complex quasi-periodic spectrum and unequal mode spacings translating from both material and cavity dispersion (see Fig. 1). Significant reduction in the mode spectral density is achieved in highly oblate spheroidal microcavity (microtorus).[23] Our present experiments shows that changing the shape of a dielectric cavity allows one to change the WGM spectrum of the cavity significantly without destroying the quality factor.

As an example, we measured WGM spectra of disc cavities with toroidally shaped rim (Fig. 2) and with conically shaped rim (Fig. 3). The toroidal geometry with its transverse curvature diameter nearly equal to the thickness of the disk, allowed to significantly rarefy the spectrum compared to a spherical layer (separate modes are visible in Fig. 2 as opposed to conglomerates in Fig. 1). However, with this geometry it was difficult to further increase the transverse curvature to eliminate all but one WGM per free spectral range: disks smaller than 100 μm in thickness were very hard to polish into toroidal shape. As an alternative to further improve the spectral regularity, we prepared a biconical cavity (Fig. 3) that was subsequently polished at the rim into a very sharp bend toroid with osculating curvature diameter of $\sim 20\ \mu$m). The spectrum proved to contain only one major mode (distinct successive peaks), and also a very high Q of 5×10^7 was obtained with this resonator, presumably because of eliminated damage to the thick (500 μm) wafer material without initial grinding of the wafer.

3. UV-ASSISTED FREQUENCY TUNING OF OPTICAL WGM CAVITIES

The experiment involved microspheres made of germanium-doped silica. We fabricated spheres using two methods. In the first case, the silica sphere was fabricated in the manner described in,[24] and was then covered by a small amount of germanium oxide powder. The sphere was subsequently heated to a controlled temperature to melt the germanium oxide, but not the silica sphere. As the germanium oxide melted, it formed a thin coating over the surface of the sphere. A small amount of germanium oxide also diffused below the surface of silica, creating a thin shell of photosensitive material. Repeating the powder-and-heat process many times, we produced germanium oxide-coated/doped spheres of sufficient photosensitivity to use in the experiments.

The approach described above is time consuming. So for a better efficiency, we used a germanate glass optical fiber with core material containing 19-20 molar percent of germanium oxide. This shortened the fabrication process, and yielded microspheres with much greater maximum change in the index of refraction.

The setup for trimming the frequency included an argon-ion laser to change the resonator frequency, a tunable 1550 nm diode laser to control the frequency shift, an erbium-doped fiber amplifier, a Fabry-Perot cavity as a frequency reference marker to stabilize the drift of the laser and to measure the spacing between the spectral lines.

The probe light at 1550 nm from a tunable laser was sent into the microsphere with an angle-polished fiber.[5] The output light was collected and sent to a photodiode that produced a spectrum of the microsphere as laser frequency was varied. The output light exits the microsphere at an angle of $5 - 15$ degrees from the direction of the incident light, so that the two beams are physically separated.[9] A second fiber with a convex tip focused the $60 - 200$ mW UV output radiation from a 351 nm argon-ion laser onto the surface of the microsphere. This radiation permanently changed the chemical structure of the microsphere material (useful permanent index-changing effect), as well as caused heating of the sphere. Both of these effects resulted in the frequency shift of WGMs. The instantaneous effect of heating was much stronger than the effect due to UV-assisted permanent shifts we were interested in. By alternately opening and closing a shutter at intervals of several seconds (simply allowing the sphere to cool down), we were able to separate the frequency shift caused by transient thermal effects from that caused by a permanent chemical change.

Fig.4 shows results from one of the experimental runs. In the germanium-oxide-coated spheres, we found the maximum resonant frequency shift of 8 GHz. In the spheres made of the uniform germanate glass, we found a maximum shift of 18 GHz, which is more than one non-azimuthal (l-m) FSR in a large ($> 100\ \mu$m diameter) sphere. This has a special significance, since shifting a spectrum by more than the FSR of the resonator provides us with the ability to engineer a resonance at any desired frequency.

4. SECOND ORDER FILTERS USING OPTICAL WGM CAVITIES

To produce second order filter based on two coupled WGM resonators we used the technique described in the previous Section. Our goal was to bring a pair of resonances in two adjacent spheres into close proximity so that their uncoupled resonance curves would overlap in the frequency domain. The set up is shown on Fig.5. The frequency of a 1550nm laser diode was current modulated by with a sawtooth signal. To increase the laser power, we use an erbium-doped fiber amplifier at the output of the laser. One half of this output was introduced into a Fabry-Perot resonator with a FSR of 20 GHz. The resonator served as a reference to correct for any laser frequency drift, and for measuring the spacing between resonance lines of the WGM cavity.

The other half of radiation from the erbium-doped fiber amplifier was introduced into an angle-polished fiber which was used as the input coupler to the first, germanium doped, microcavity. We placed a second microcavity nearby the first one, and positioned it so that the equators of the cavities were coupled via the evanescent field. A second angle-polished fiber served as an output coupler. Couplers and spheres were placed on miniature PZT

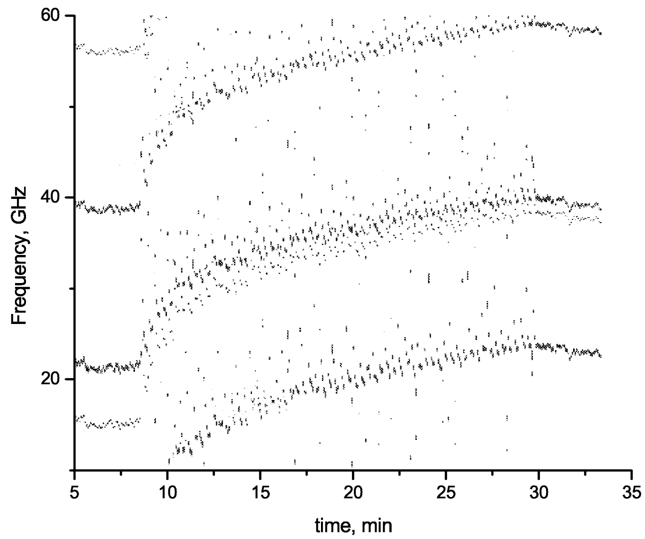


Figure 4. Resonance frequency shifts as a function of exposure by 600 mW 351 nm UV laser radiation

translators so we could manage the coupling between them. For the optimal tuning of the positions of the cavities the probe light passed through both spheres with less than a 3 dB fiber-to-fiber loss. The light from the output coupler was sent to a photodiode, so that a plot of current versus time was obtained as the frequency spectrum of the combined system. Finally, the fiber with a convex tip focused the output of an UV argon-ion laser onto the surface of the first resonator to allow a permanent shift of the resonator modes.

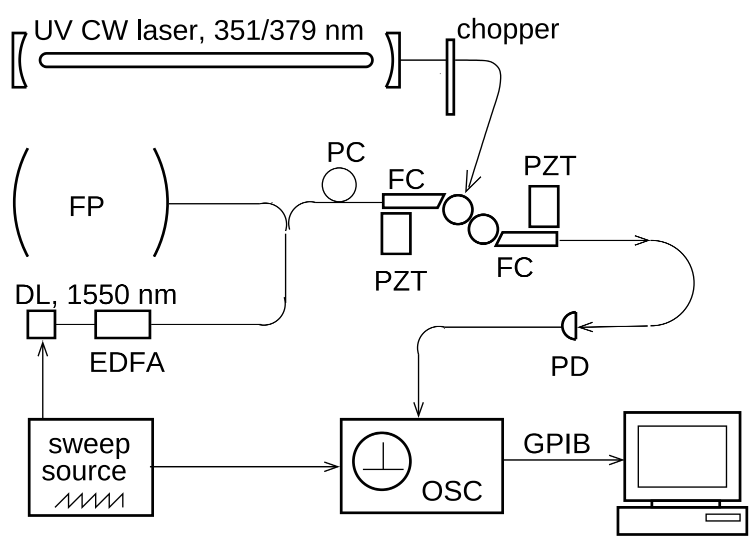


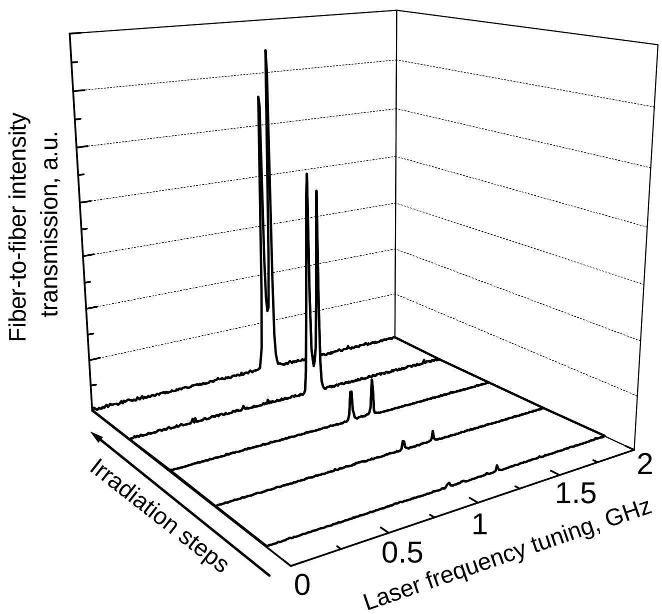
Figure 5. Installation to fabricate a second order filter

The first resonator was made from germanate glass silica, the core material from a germania-doped optical fiber. We used both spherical and toroidal resonators. Toroidal resonators are more difficult to fabricate, but they have the advantage of a much sparser frequency spectrum.[23] This occurs because microtorus WGMs with trajectories localized far from the equatorial plane of the cavity have high losses and, therefore, are effectively removed from the resonator's spectrum.

Microspheres made of pure silica were used as the second microcavity. They had approximately the same diameter as the first cavity. The mode structure of the second cavity remained unchanged throughout the experiment, within the resolution of our observation, despite some exposure by small amounts of reflected and refracted UV light. Pure silica does possess some very small UV photosensitivity; however it is much smaller than that of germanate glass and has not affected the results of our experiments.

The differences in the size of the cavities is rather important. Our aim was to produce spectral lines of both resonators of a similar width to allow the realization of a complex spectral line structure. If resonances of two interacting cavities have differing widths, then as they are made to approach one another, the height of the narrower resonance will simply track the shape of the wider one, which is of no use for the filter application. The size of a cavity affects the quality of its resonance since cavities of similar size have similar quality factors.

Before starting the experiment, we first arranged for the maximum efficiency in the photochemical process to shorten the time of the experiment. The maximum efficiency occurs when the UV light is focused just inside the equator of a doped sphere (or a torus), at a point where the WG modes have a large field intensity. To achieve this, we first tuned the argon-ion laser to the 379 nm line. Laser radiation at this wavelength affects the chemistry of the material, but the process is relatively slow, so the overall effect can be made negligible if the exposure time is kept short. Nonetheless, the absorbed UV in the material results in thermal expansion, which produces a visible shift in the resonance frequencies. If the position of the UV fiber is adjusted such that the thermal shift in the frequency spectrum is a maximum, then the UV light is properly focused at the point of maximum efficiency.



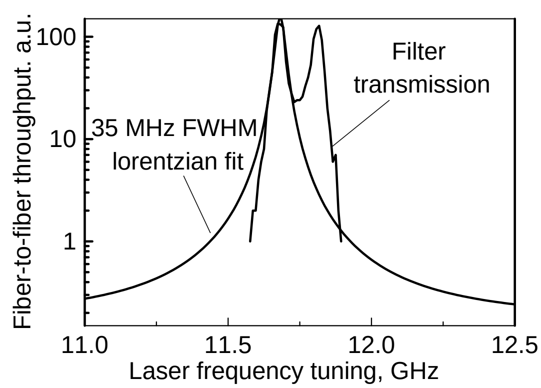


Figure 6. Filter spectrum. Thin line depicts experimental results, thick line - Lorentzian fit

After proper alignment, the UV laser was tuned to 351 nm, which is the most photochemically efficient wavelength generated by our argon laser. To be sure that the system is stable, several data points were first taken with the UV beam blocked. Subsequently, a strobe technique was used by alternately opening and closing a shutter at intervals of several seconds to track small changes of the WGM spectra. In this way, the frequency shift caused by the transient thermal effects can be separated from shifts caused by a permanent chemical change.

Fig.6 depicts the final spectrum obtained in the experiment with a germanium-doped microtorus and a pure-silica sphere. To highlight the filter performance we plotted also the Lorentzian fit of the curve. We see, that the two-cavity filter has much faster rolloff compared with the Lorentz line. On the other hand, the filter function does not look exactly like second order one because of small microcavities overcoupling.

Transmission and reflection of monochromatic electromagnetic wave of frequency ω by a WGM optical lossless resonator may be characterized by coefficients

$$T = \frac{\gamma}{\gamma + i(\omega - \omega_0)}, \quad R = \frac{i(\omega - \omega_0)}{\gamma + i(\omega - \omega_0)}, \tag{1}$$

where T and R describe the amplitude transmission and reflection respectively, γ and ω_0 are the linewidth and resonance frequency of a mode of the resonator (we assume that $|\omega - \omega_0|$ is much less than the cavity free spectral range). The power transmission $|T|^2$ through the resonator is Lorentzian.

When two cavities are placed in series, the light amplitude transmission coefficient is

$$T_{12} = \frac{T_1 T_2}{1 - R_1 R_2 \exp(i\psi)}, \tag{2}$$

where T_j and R_j $(j = 1, 2)$ are the transmission and reflection coefficients of the resonators, and ψ is the phase shift introduced by the coupling.

Let us consider the case of resonators with slightly different resonance frequencies ω_1 and ω_2 and the same linewidth γ, and assume that $\exp(i\psi) = -1$. The power transmission through the system is

$$|T_{12}|^2 = \frac{\gamma^4}{\gamma^4 + \gamma^2(\omega_1 - \omega_2)^2 + 4(\omega - \omega_1)^2(\omega - \omega_2)^2}. \tag{3}$$

One can see from Eq. 3 that the transmission through is small for any frequency when the resonant frequencies of the modes are far from each other ($|\omega_1 - \omega_2|^2 \gg \gamma^2$). The transmission value has two resonance increases corresponding to the partial resonances of each mode. The transmission becomes close to unity when the mode frequencies are close to each other compared with the modes' width γ. Finally, the transmission for the off resonant tuning is inversely proportional to ω^4, not to ω^2, as for a single resonator, Lorentzian, filter. Those are the properties of the second order filters; they perfectly much our experimental observations.

5. TUNABLE FILTERS BASED ON OPTICAL WGM CAVITIES

In the previous sections we have discussed filters created with UV assisted permanent tuning of the WGM spectra of a germanate glass microcavity. Let us now focus on the possibility of an electrically controlled tuning of the WGM spectra of a dielectric microresonator. This can be realized, for instance, with disk cavities fabricated from lithium niobate wafers.

A schematic diagram of the tunable filter configuration is shown in Fig.7. A Z-cut disk resonator has in $d = 4.8$ mm diameter and 170 μm in thickness.[25] The resonator perimeter edge was polished in the toroidal shape with 100 μm curvature radius. We studied several nearly identical disks. The repeatable value of the quality factor of the main sequence of the resonator modes was $Q = 5 \times 10^6$ (the observed maximum was $Q = 5 \times 10^7$), which corresponds to 30 MHz bandwidth of the mode.

Light was sent into, and retrieved out of, the resonator via coupling diamond prisms. The repeatable value of fiber-to-fiber insertion loss was 20 dB (the minimum measured insertion loss was approximately 12 dB). The maximum transmission was achieved when light was resonant with the resonator modes. Tuning of the filter is achieved by applying voltage to the top and bottom disk surfaces coated with a conducting material. The coating is absent on the central part of the resonator perimeter edge where WGMs are localized.

The maximum frequency shift of the TE and TM mode may be found from[26]

$$\Delta\nu_{TE} = \nu_0 \frac{n_e^2}{2} r_{33} E_Z, \quad \Delta\nu_{TM} = \nu_0 \frac{n_o^2}{2} r_{13} E_Z, \tag{4}$$

where $\nu_0 = 2 \times 10^{14}$ Hz is the carrier frequency of the laser, $r_{33} = 31$ pm/V and $r_{13} = 10$ pm/V are the electro-optic constants, $n_e = 2.28$ and $n_o = 2.2$ are the refractive indexes of $LiNbO_3$, E_Z is the amplitude of the

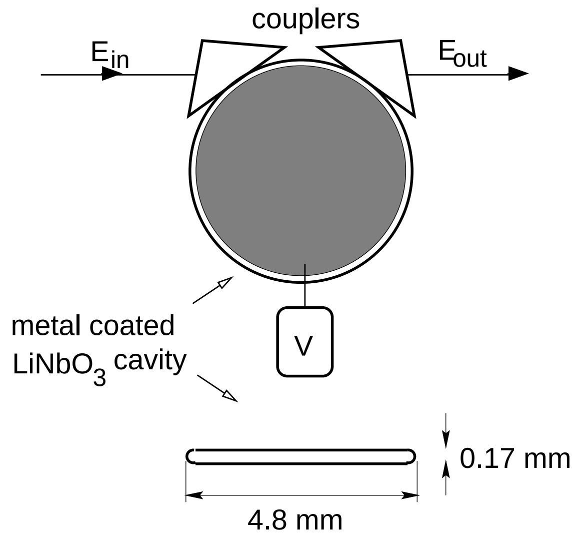


Figure 7. Filter setup. The lithium niobate disc resonator is coated with indium.

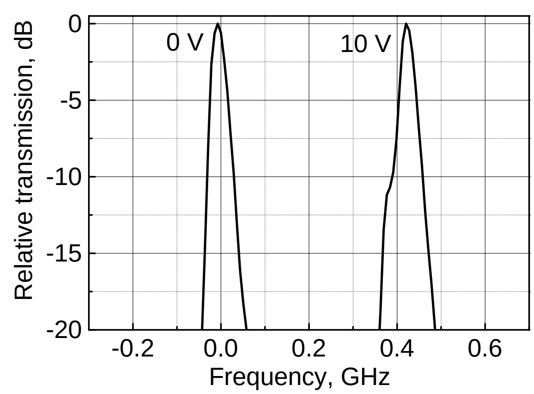


Figure 8. Transmission characteristics of the filter. The maximum transmission corresponds to 12 dB attenuation of the input signal.

electric field applied along the cavity axis. We worked with TM modes because they have better quality factors than TE modes. If the quality factor is not very important, it is better to work with TE modes because their electro-optic shifts are three times as much as those of TM modes for the same values of applied voltage.

Experimentally measured electro-optic tuning of the filter spectral response and tuning of center wavelength with applied voltage is shown in Fig.8. The filter exhibits linear voltage dependence in ± 150 V tuning range, i.e. the total tuning span exceeds the FSR of the resonator. Changing the tuning voltage from zero to 10 V shifted the spectrum of the filter by 0.42 GHz for TM polarization, in agreement with theoretical value. This value does not depend on the resonator properties and is related to the fundamental limitations of optical resonator based high speed electro-optical modulators.[27]

It is interesting to note that $\Delta\nu(E_Z)$ had a hysteresis feature for large enough DC electric field ($E_Z > 2\text{MV/m}$) applied to the resonator. The time varying voltage results in an incomplete compensation of the mode shift, i.e. $\Delta\nu(E_Z = 0) \neq 0$ (see in Fig. 9). The effect has some similarities with bias drift in early lithium niobate electro-optical modulators.[28] The maximum observed frequency tuning of the filter in the nonlinear regime was approximately 40 GHz, for 75μm thick disc cavity.

We see a possible explanation of the hysteresis in an accumulation of residual charges on the surface of the

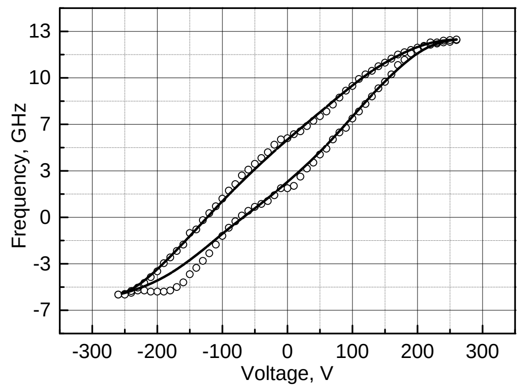


Figure 9. A dependence of position of a WGM resonance on the voltage applied to a disc cavity. The cavity thickness is approximately 170 μm. The line is a guide for eyes.

crystal. The origin of the hysteresis may also be related to the switching properties of domain direction in $LiNbO_3$ crystal.[29] Application of an electric field along the Z-axis of the crystal results in orientation switching of crystal domains. It occurs when the externally applied field has a comparable strength ($E_{in} \approx$ 3MV/m,[29]), and an opposite direction, with those of the crystal field. The properties of the hysteresis behavior need additional careful study and will be discussed elsewhere.

The insertion loss in our scheme occurs primary due to inefficient coupling to the WGM. We believe that antireflection coating of the coupling prisms or use of special gratings placed on high-index fibres may reduce the losses significantly.

To demonstrate the filter performance, we have configured it as a photonic microwave filter for transmission of a video signal at a microwave band. This type of narrow-band microwave signal link may be important for the development of portable navigation and communication devices at millimeter-wave band frequencies, that can provide significantly higher capability to the NASA space missions. For example, photonic architecture allows one to create a uniform technological platform for RF through millimeter-wave systems, that would otherwise require different sets of bulky and expensive hardware if implemented directly at RF frequencies.

The scheme of our transmission experiment is shown in Fig.10. A video signal with approximately 20 MHz FWHM bandwidth and zero carrier frequency was sent from a CCD camera to a mixer, where it was mixed with a 10 GHz microwave carrier. The resultant modulated microwave signal was transmitted to a microwave receiver, filtered to suppress higher harmonics, amplified, and upconverted into light using a Mach-Zehnder electro-optic modulator. The modulated signal was then sent through our filter, heterodyned and detected with a fast photodiode. The microwave field from the photodiode output was mixed with a microwave carrier to restore the initial signal.

High-Q WGM cavity may cause mixing of the amplitude and phase fluctuations of the light. The amplitude of the transmitted light through the filter may be presented as

$$E_{out}(t) \approx \frac{\widetilde{E}_{in}(t-\tau_d)e^{-i\omega t}\gamma}{\gamma + i(\omega - \omega_0 + \dot{\phi}_{in}(t))}, \tag{5}$$

where $\widetilde{E}_{in}(t-\tau_d)$ is the slow field amplitude, τ_d stands for the group delay, $\dot{\phi}_{in}(t)$ results from the phase diffusion of the pump laser. The filter works well when the phase diffusion of the pump laser is small $\gamma \gg \dot{\phi}_{in}(t)$. The filter transforms the phase fluctuations of the laser into the amplitude fluctuations for the large phase diffusion.

It is important to note that to characterize the filtered signal and retrieve encoded information the filter output should be mixed with a monochromatic light and detected with a photodiode. The filter contains a high-Q cavity that introduces group delay τ_d into the signal. This group delay results in an additional source

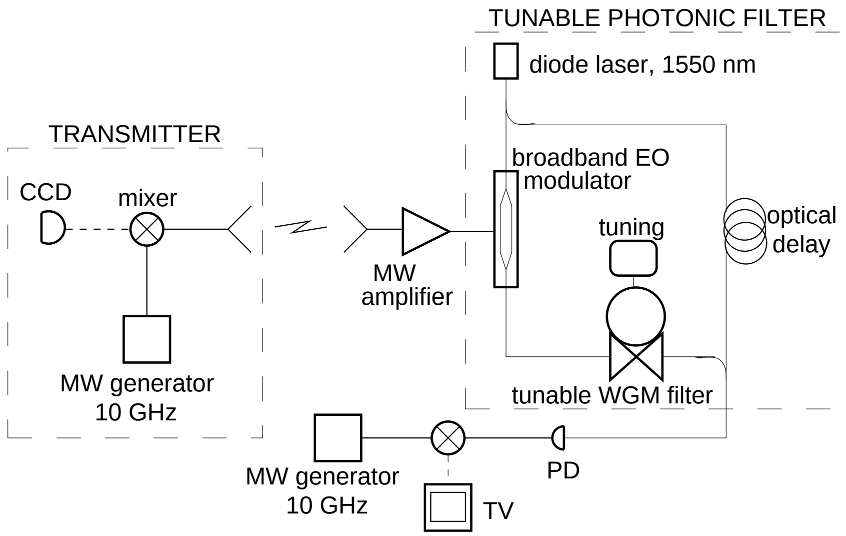


Figure 10. Schematic diagram of the video signal transmission experiment. Solid thin line corresponds to optical fibers, solid thick lines to microwave waveguides, and dashed lines - electric circuits.

of frequency-to-amplitude noise conversion when the output signal from the filter is mixed with the light that did not pass through the filter. This happens unless the scheme is balanced. We inserted the filter into a Mach-Zehnder configuration with a fiber delay line L_f to compensate for the group delay. Delay line length was equal to $L_f = n_o dF/2n_f = 1.2$ m , where $n_f \simeq 1.5$ is the refractive index of the fiber material and $F = 300$ is the cavity finesse. Such a compensation is not required if the laser linewidth is much smaller than the width of the cavity resonance. In our case optical characterization of the filter was achieved using a semiconductor diode laser with a 30 MHz FWHM line, which is quite large. The laser power in the fiber was approximately 2.5 mW.

6. CONCLUSION

We have demonstrated several techniques for precise engineering of the whispering gallery mode resonance frequencies of dielectric microresonators. Depending on the dielectric nature we were able to produce permanent or temporal shifts of the whispering gallery mode spectrum. Our methods are important in applications where high-Q microresonators of specific resonance frequency are desired. In one pproach, we have demonstrated a new technique for tuning the resonance of a germania-doped silica microresonator to produce a coupled system of two microresonators. Such a system is basically a second order filter with a sharp rolloff. The technique may also be used to produce other complex filter functions with any desired line shapes. In a second approach, we realized a tunable filter that uses high-Q whispering gallery modes excited in a disk-shaped lithium niobate resonator. The filter may be utilized for high-density telecommunication networks, and in RF photonics applications. Our experimental results are in an agreement with theory.

7. ACKNOWLEDGMENTS

The work reported in this article was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA and with National Research Council support.

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